High-Energy Infrared Soliton Dynamics in Hollow Capillary Fibres

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Abstract: We demonstrate soliton self-compression of high-energy 1800 nm laser pulses in hollow capillary fibres. This enables generation of infrared attosecond pulses and few-femtosecond pulses from the deep ultraviolet to the infrared with resonant dispersive wave emission.

Ultrafast laser pulses in the infrared spectral region are important tools in optical science, particularly in driving frequency conversion processes. Two of the most prominent applications are X-ray high-harmonic generation and the conversion to widely tuneable femtosecond pulses in the ultraviolet and visible. In the former, few- and sub-cycle pulses are especially useful, but existing compression techniques are limited by the materials used for bulk dispersion compensation. In the latter, multi-stage conversion in nonlinear crystals limits both the conversion efficiency and the achievable pulse duration. Here we demonstrate that soliton self-compression of 30 fs laser pulses at 1800 nm in a hollow capillary fibre (HCF) enables the generation of both the shortest infrared laser pulses ever created and highly energetic few-femtosecond pulses from the deep ultraviolet to the near infrared with high efficiency.

In the experiment, we couple 30 fs full width at half-maximum (FWHM) laser pulses at a central wavelength of 1800 nm into a 2.5 m long argon-filled HCF with a core diameter of 450 μm [1]. The spectrum of the pulses exiting the HCF is analysed by a double spectrometer system covering 200 nm to 2550 nm. We characterise the pulses using ultrabroadband sum-frequency generation time-domain ptychography (TDP) [2] with a phase-matching window from 350 nm to beyond 3000 nm. The pulse profile at the HCF exit is reconstructed by numerical back-propagation of the retrieved pulses.

Fig. 1 shows the measured pulse at the HCF exit when filling the HCF with 490 mbar of argon and driving with 290 μJ of energy. The excellent agreement between the measured and retrieved TDP traces as well as between the measured and retrieved spectra shows that the retrieval was successful. The pulse has self-compressed to an envelope duration of 2 fs FWHM with a peak power of 27 GW. The electric field transient that this pulse represents is shown in the inset in Fig. 1(a). The FWHM duration of the squared field is 840 as and the central wavelength around the pulse peak is 1340 nm.

Resonant dispersive wave (RDW) emission driven by soliton self-compression is a powerful technique for the generation of tuneable few-femtosecond pulses, both at low energy in hollow-core microstructured fibres [3] and at high energy in HCF [4]. When driving at 800 nm, however, phase-matching and the requirement for anomalous

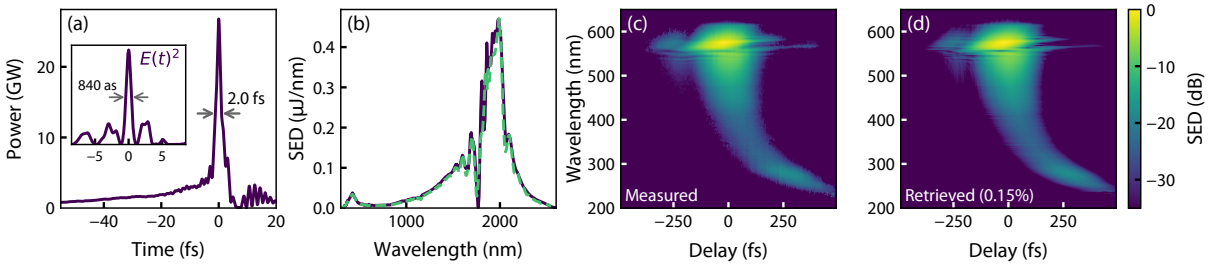

Fig. 1. TDP measurement of the self-compressed pulse at 470 mbar of argon pressure. (a) Temporal profile of the pulse. The FWHM duration of the pulse is 2 fs. The pulse contains 211 μJ of energy and its peak power is 27 GW. The inset shows the square of the electric field around the peak of the pulse; its FWHM duration is 840 as. (b) Spectral energy density (SED) of the pulse from the TDP measurement (purple) and measured directly (green dashed). (c) Measured TDP trace on a logarithmic colour scale after marginal correction. (d) Retrieved TDP trace on the same colour scale. The RMS error between the traces is 0.15%.

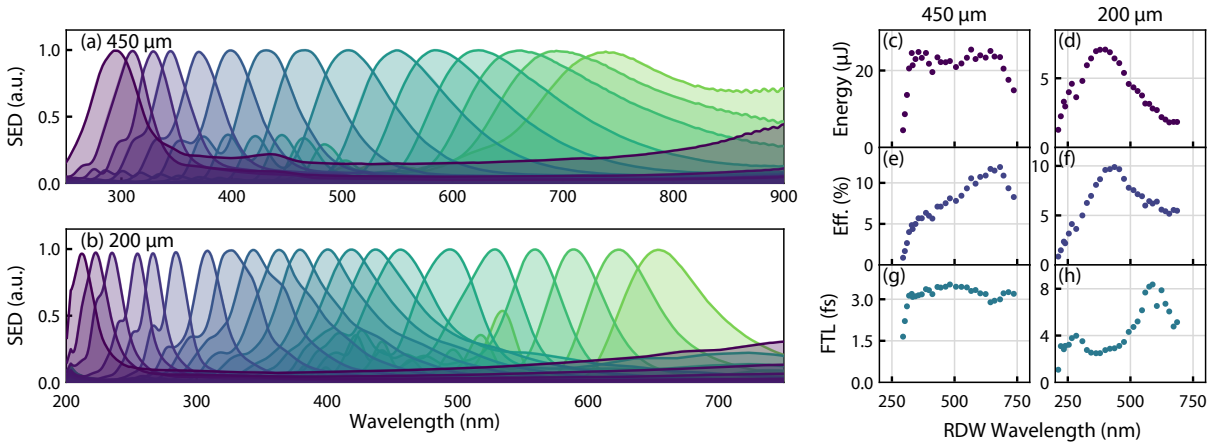

Fig. 2. (a) RDW spectra generated in the first HCF with 450 µm core diameter. Each spectrum is normalised to the peak in the wavelength region shown. The argon pressure required for the generation ranges from 255 mbar (shortest wavelength) to 1330 mbar (longest wavelength). (b) RDW spectra generated in the second HCF (200 µm core diameter) when driven with 16 fs pulses generated in the first HCF. The pressure varies from 470 mbar (shortest wavelength) to 7000 mbar (longest wavelength). (c-d) Energy, (e-f) conversion efficiency, and (g-h) FTL duration of the RDWs shown in (a) and (b).

dispersion at the pump wavelength limit the tuneability range so that only part of the visible region can be covered. By moving to 1800 nm driving, we generate highly energetic pulses tuneable from the deep ultraviolet (210 nm) to the near infrared (740 nm).

Fig. 2 shows RDW spectra generated in two different configurations. Firstly, we generate pulses tuneable from 300 nm to 740 nm directly in the 450 µm HCF. Here, the pulse energy is around 25 µJ over most of the tuning range. The spectra support pulse durations of just over 3 fs (as shown previously in microstructured fibre, the use of a pressure gradient allows delivery of near transform-limited RDW pulses to a target [5]). Secondly, we use the self-compressed pulses (16 fs) from the first HCF to drive RDW emission in a second stage with a smaller (200 µm core diameter) and shorter (38 cm length) HCF. Using less than 200 µJ of input energy, we generate pulses tuneable from 210 nm to 700 nm with up to 7.5 µJ of energy. Such a compact and energy-efficient system will be particularly useful for the emerging field of X-ray pump-probe spectroscopy, where the energy demands of high-harmonic generation and timing stability requirements for attosecond time resolution are key challenges.

Our work extends the concept of optical attosecond pulses to the infrared spectral region, where such extreme pulse durations have not been achieved using any other method. Furthermore, we show that RDW emission driven by infrared laser pulses overcomes some of the key limitations of conventional tuneable frequency conversion, allowing for the efficient generation of extremely widely tuneable few-femtosecond pulses—an ideal source for the next generation of advanced spectroscopy.

References

1. C. Brahms, F. Belli, and J. C. Travers, "High-energy infrared soliton dynamics in hollow capillary fibres," arXiv:1910.10458 [physics] (2019).
2. T. Witting, D. Greening, D. Walke, P. Matia-Hernando, T. Barillot, J. P. Marangos, and J. W. G. Tisch, "Time-domain ptychography of over-octave-spanning laser pulses in the single-cycle regime," Opt. Lett. **41**, 4218–4221 (2016).
3. K. F. Mak, J. C. Travers, P. Hölzer, N. Y. Joly, and P. S. J. Russell, "Tunable vacuum-UV to visible ultrafast pulse source based on gas-filled Kagome-PCF." Opt. Express **21**, 10942–53 (2013).
4. J. C. Travers, T. F. Grigorova, C. Brahms, and F. Belli, "High-energy pulse self-compression and ultraviolet generation through soliton dynamics in hollow capillary fibres," Nat. Photonics **13**, 547–554 (2019).
5. C. Brahms, D. R. Austin, F. Tani, A. S. Johnson, D. Garratt, J. C. Travers, J. W. G. Tisch, P. S. Russell, and J. P. Marangos, "Direct characterization of tuneable few-femtosecond dispersive-wave pulses in the deep UV," Opt. Lett. **44**, 731 (2019).